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NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS

TECHNICAL NOTE 3766

RADIATION AND RECOVERY CORRECTIONS AND TIME CONSTANTS OF SEVERAL CHROMEL-ALUMEL THERMOCOUPLE PROBES IN HIGH-TEMPERATURE, HIGH-VELOCITY GAS STREAMS

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Cleveland, Ohio

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SUMMARY

Radiation and recovery corrections and time constants were experimentally determined for several designs of shielded and unshielded thermocouple probes using chromel-alumel wire. Radiation and time constant data were obtained for Mach numbers from 0.3 to 0.9, static pressures from $\frac{2}{3}$ to $1\frac{1}{3}$ atmospheres, and temperatures from 1500° to 2500° R. Recovery data were obtained for Mach numbers from 0.2 to 0.9 and static pressures from $\frac{1}{7}$ to $1\frac{2}{3}$ atmospheres, at room total temperature. A review of the theory of gas temperature measurements and an analysis of the data show that simple empirical formulas can be used to correlate corrections for various gas-stream conditions. Tables and graphs are presented which show the correction factors of the various designs to aid in selecting a probe for a particular application.

INTRODUCTION

In performance studies of jet engines, accurate knowledge of the gas temperature at the combustor outlet and in the tailpipe is frequently required. Thermocouple probes are conventional instruments for such measurements; however, with these probes, corrections of relatively large magnitude are often necessary. This necessity results from the fact that a body immersed in a high-temperature, high-velocity gas stream generally attains thermal equilibrium at a temperature different from that of the gas. For a thermocouple probe immersed in a low-velocity gas at steady-state conditions, a heat balance exists between the convective heat transfer from the gas to the probe and the radiation and conduction between the probe and external surroundings. At higher velocities an additional factor becomes important, namely, the aerodynamic heating effect. The effects of the various factors which contribute to the inability of the thermocouple to indicate total temperature may be expressed in terms of corrections to be applied to the temperature indication.

These corrections may be termed "radiation and conduction corrections", which account for the external heat-transfer effects, and "recovery corrections", which account for the internal heat-transfer and aerodynamic heating effects.

For transient conditions, a characteristic "time constant", associated with a given probe, is also involved. Various investigators have evaluated these quantities for many different probe designs. Reference 1 is a comprehensive bibliography of the subject; reference 2 is a more recent work that presents some of the considerations in the selection of probes for jet-engine temperature measurements. For a given application a compromise of desirable probe characteristics is usually necessary (ref. 2). The present work is concerned with the experimental evaluation of several probe designs, hitherto unreported, along with some standard designs which have found considerable application at the NACA Lewis laboratory. This work is part of the high-temperature-measurements research program being conducted at the Lewis Flight Propulsion Laboratory.

SYMBOLS

c_w	specific heat of thermocouple wire
d	diameter of wire
h_c	convective heat-transfer coefficient
K^*_{rad}	radiation-correction coefficient
M	Mach number
P	total pressure
p	static pressure
q	heat-transfer rate
q_r	radiant heat-transfer rate
q_s	heat-storage rate
T_t	total temperature
T_d	equivalent duct temperature
T_g	temperature of gas surrounding junction

T_w indicated junction temperature

t time

Δ recovery-correction factor, $(T_t - T_g)/T_t$

ε_w emittance of wire

ρ_w density of thermocouple wire

σ Stefan-Boltzmann constant

τ time constant

τ_0^* reference time constant

Subscripts:

c convective

f final

i initial

k conductive

w thermocouple wire

0 reference

THEORY

The indication of a temperature probe, in a high-temperature high-velocity gas, is the result of a balance among various modes of heat transfer. In general, one may write

$$q_c + q_r + q_k + q_s = 0 \tag{1}$$

where q_c is the rate of convective heat transfer between the gas stream and the junction, q_r is the rate of net radiant heat exchange between the junction and the surroundings, q_k is the rate at which heat is conducted out of the junction through the thermocouple wire, and q_s is the rate of heat storage in the junction.

It may be concluded that steady-state gas temperatures may be obtained by adding radiation, conduction, and recovery corrections to the thermocouple indication, and that the transient behavior of a thermocouple may be characterized by a parameter termed the time constant.

The detailed equations for the particular case of a bare-wire thermocouple are developed in reference 3 and summarized in reference 2. Reference 2 postulates that, for other probe designs, it is possible to write

$$q_c \propto h_c(T_g - T_w) \tag{2}$$

$$q_r \propto \sigma\varepsilon_w(T_d^4 - T_w^4) \tag{3}$$

and

$$q_s \propto \rho_w c_w \frac{\partial T_w}{\partial t} \tag{4}$$

where the constants of proportionality are functions of the geometries of the junction and probe. It is further postulated that the convective heat-transfer coefficient h_c is proportional to the square root of the Reynolds number based on the wire diameter and on the gas properties at wire temperature. Therefore, expressions for radiation corrections and time constants for these other probe designs can be derived that are similar in algebraic form to the radiation-correction and time-constant formulas for the bare-wire design treated in reference 3. The equations derived in references 2 and 3 are for a standard temperature of 519° R. For ease of computation, in the present report the equations are modified in order to use a reference temperature of 1000° R. These equations can be written as follows:

$$\text{Radiation correction} = \frac{K_{rad}^*}{\sqrt{Mp}}\left(\frac{T_w}{1000}\right)^{-0.18}\left[\left(\frac{T_w}{1000}\right)^4 - \left(\frac{T_d}{1000}\right)^4\right] \tag{5}$$

and

$$\tau = \frac{\tau_0^*}{\sqrt{Mp}}\left(\frac{T_w}{1000}\right)^{-0.18} \text{ (sec)} \tag{6}$$

where temperatures are in °R and pressure p is in atmospheres.

Evaluation of the terms K_{rad}^* and τ_0^* for a bare wire in crossflow from relations in reference 3 yields

$$K_{rad}^* \approx 27\varepsilon_w\sqrt{d} \tag{7}$$

and

$$\tau_0^* \approx 1.2\rho_w c_w\, d^{3/2} \tag{8}$$

where ρ_w is in pound mass per cubic foot, c_w is in Btu per pound mass, and d is in inches. (The radiation-correction coefficient K^*_{rad} is 0.89×10^{12} times the quantity K_{rad} used in reference 2; τ^*_0 is 0.89 times the quantity τ_0 also used in reference 2.)

The validity of the assumptions leading to equations (5) and (6) is subject to experimental confirmation that the quantities K^*_{rad} and τ^*_0 are indeed constant over wide ranges of M, p, and T_w. If this fact were established, such experiments could also give empirical values of the constants that would be more reliable than the values which were established in reference 2 through a combination of experimental data and intuitive theoretical assumptions. The experiments described herein do provide such empirical information.

The conduction correction is not considered separately in this report, because the test method did not distinguish between radiative and conductive modes of heat loss, and because computation indicates that the conduction correction is a minor portion of the combined heat-loss correction.

In using thermocouple probes, it is convenient to correct for an aerodynamic recovery error by using a recovery-correction factor Δ where

$$\Delta = \frac{T_t - T_g}{T_t} \tag{9}$$

The quantity Δ is primarily a function of the Mach and Reynolds numbers. Reference 4 shows that for cylinders in crossflow with diameters between 0.010 and 0.040 inch

$$\frac{\Delta}{\Delta_0} = \left(\frac{p}{p_0}\right)^{1/5}\left(\frac{T_0}{T_t}\right)^{1/4}\left(\frac{d}{d_0}\right)^{1/5} \tag{10}$$

where Δ_0, as a function of the Mach number, is determined for a reference diameter d_0 at reference values of the pressure p_0 and the temperature T_0.

Data, which suggest that similar expressions might be empirically established for other probe configurations, are presented in reference 5. This reference suggests that the exponent of (p/p_0) is about -0.8 for various shielded designs and -0.1 for an unshielded wedge.

For conditions where the conduction error is negligible, equations (5) and (9) may be combined to give the total temperature of the gas T_t in terms of the junction temperature T_w. Then

$$T_t = \left\{T_w + \frac{K^*_{rad}}{\sqrt{Mp}}\left(\frac{T_w}{1000}\right)^{-0.18}\left[\left(\frac{T_w}{1000}\right)^4 - \left(\frac{T_d}{1000}\right)^4\right]\right\}\left(\frac{1}{1 - \Delta}\right) \tag{11}$$

or, approximately, since $\Delta << 1$,

$$T_t \approx T_w + \left\{\frac{K^*_{rad}}{\sqrt{Mp}}\left(\frac{T_w}{1000}\right)^{-0.18}\left[\left(\frac{T_w}{1000}\right)^4 - \left(\frac{T_d}{1000}\right)^4\right]\right\} + T_w\Delta \tag{12}$$

In the experiments reported herein, the approximation (12) was adequate.

APPARATUS AND PROCEDURE

Probe Descriptions

A photograph and detailed drawings of the probes tested are shown in figures 1 and 2, respectively. Probe 1 was used in the tests as a standard or reference probe for reasons discussed in the next section; probes 2, 3, and 4 were included for purposes of comparison. Probes 5, 6, 7, 8, and 9 were designed for special test applications at this laboratory. All probes had chromel-alumel elements. Some probes were constructed with solid ceramic insulators and others used swaged magnesium-oxide insulation. Four probes of each type were constructed for these tests, in order to provide greater assurance that the results were representative of the respective designs.

Probe 1 is a sonic-aspirated thermocouple similar to those reported in reference 6. Probe 2 is a platinum-shielded thermocouple such as described in reference 7. Probe 3 is a semi-shielded thermocouple (ref. 8), and probe 4 is a bare-wire crossflow probe (ref. 2). Probe 5 is an unshielded configuration in which the wires were welded and shaped to form a wedge. Probe 6 has an element identical to that of probe 5, enclosed in a single stagnation shield. Probe 7 has a wedge-shaped element enclosed in a venturi-shaped shield. Probes 8 and 9 have elements enclosed in a stagnation shield, which in turn is enclosed in another shield with provision for aspirating the hot gases between the two shields. Probe 8 is a smaller version of probe 9, but it has some construction changes, which are shown in the detailed drawings of figure 2(h).

Test Methods and Accuracy

The tests were performed in the high-temperature tunnel with an Inconel combustor section (ref. 9). This facility is capable of producing Mach numbers from 0.2 to 1.0 at temperatures from 1000° to 3500° F and pressures from 1/2 to 2 atmospheres. The arrangement at the test section is shown schematically in figure 3. Radiation and time-response data were obtained for Mach numbers from 0.3 to 0.9, static pressures from $\frac{2}{3}$ to $1\frac{1}{3}$ atmospheres, and temperatures from 1500° to 2500° R. The radiation corrections of probes 2 to 9 were determined by comparing the probe readings with those of the sonic-aspirated probe 1, the latter probe being virtually free from radiation errors (ref. 6). This comparison was done at any given condition of airstream temperature, pressure, and velocity, by moving each probe to the same location in the gas stream. This procedure was used because slight temperature and velocity gradients existed in the jet cross section under certain flow conditions.

Time constants were determined by suddenly inserting the test probes into the gas stream by means of the pneumatic actuator, shown in figure 3, and recording the temperature change with time. These tests were made in conjunction with the radiation-correction determinations; hence, the same range of test conditions was covered.

The recovery corrections were obtained in a variable-density tunnel, the apparatus and instrumentation for which are described in reference 5. Recovery data were obtained for Mach numbers from 0.2 to 0.9 and total pressures from $\frac{1}{7}$ to $1\frac{2}{3}$ atmospheres, at room total temperature.

The internal accuracy of the high-temperature tests was estimated from the following considerations: The thermocouple wire had a calibration tolerance of 0.4 percent. The recording potentiometer had a limit of error equivalent to 6° F. The probable error of the recovery constant determination for the sonic-aspirated thermocouple probe was estimated to be 0.5 percent; this error arises from displacement of the thermocouple junction relative to the nozzle throat because of the thermal expansion and uncertainty of the temperature effect on the ambient recovery correction. Assuming that probable errors of wire calibration and potentiometer indication are about half of the limits of error, the resultant probable error is about 0.7 percent of the absolute temperature.

The radiation corrections were obtained by taking the difference between the temperatures of the sonic thermocouple and the probe under test conditions after the indications of each were corrected for recovery effects. The factor K_{rad}^{*} was then calculated by using equation (5). In determining the most probable value of K_{rad}^{*}, more weight was given to the data in which the difference of $T_g - T_w$ was greater than the probable error 0.007 T_t; these data for a given probe were obtained in tests at high temperatures and relatively low velocities and pressures. A weighting factor $\left[(T_g - T_w)/0.007\right]^2$ was used for this purpose.

RESULTS

Radiation Corrections

For probes 2 to 7 the factor K_{rad}^{*} appeared to be constant within the scatter of the data. The weighted mean values of K_{rad}^{*} are listed in table I; the uncertainties shown are the weighted average deviations from the mean. For a bare-wire crossflow probe a theoretical value of K_{rad}^{*} ranges from 3.4 to 3.9, assuming emittances for chromel-alumel of 0.7 to 0.8; thus, the experimental value (3.6 ±0.4) for K_{rad}^{*} obtained for probe 4 is consistent with the theory. The value of K_{rad}^{*} obtained for the platinum-shielded thermocouple, probe 2, is in good agreement wi the value calculated from data given in reference 7. Total temperature obtained with probe 9 agreed with total temperature obtained with the sonic-aspirated probe (probe 1) within the experimental accuracy of the high temperature tests. The smaller double-shielded aspirated probe (pr 8) exhibited a radiation error on the order of 3/4 percent at 2500° R.

The resultant radiation corrections for probes 2 to 9 in a typical set of stream conditions are shown in figure 4. It should be noted tha the radiation corrections for the unshielded probes would be reduced by a factor of 3 if platinum rhodium - platinum wire was used instead of chromel-alumel.

Time Constants

For probes 2 to 7, the factor τ_0^{*} similarly appeared to be constant. The mean values of τ_0^{*} are also shown in table I. For the bar wire crossflow thermocouple, probe 4, the experimental value 0.40 ±0.0 was obtained. The theoretical value of τ_0^{*} from reference 3 was 0.43.

The transient response of aspirated probes 8 and 9 showed a marked deviation from a first-order system, and the time required to attain 63 percent of the step change ranged from 0.3 to 0.7 second for probe 8, and 0.6 to 1.4 seconds for probe 9, in the range of test conditions. Since the probes are aspirated, these time constants are not directly related to free-stream conditions by a relationship such as shown in equation (6). An explanation of the marked deviation from a first-order system lies in the consideration that the response of the probe involves the combined response of the thermocouple and the two radiation shields, with each subject to different flow conditions. A typical time-response record is shown in figure 5. The general shape of the curve indicates a rapid initial response and then a slower response to the final temperature level. This latter part of the curve is probably influenced most by the slower response of the shields which are of a considerably greater mass than the thermocouple.

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Recovery Corrections

The reference recovery correction factor Δ_0 varies with Mach number (fig. 6); these data were obtained at a total temperature of 540° R and atmospheric total pressure. The crosshatched regions represent the spread in data for several probes. The values of Δ_0 shown for probes 1, 8, and 9 are for critical-pressure-ratio aspiration; the recovery correction is independent of the free-stream Mach number.

The variation of the recovery-correction factor with pressure is shown in figure 7. Table II shows the combined effects of Mach number and pressure on the recovery correction.

For a cylindrical wire in crossflow, the recovery correction varies slightly with Reynolds number (ref. 4). In terms of experimentally determined quantities, this implies a variation with pressure and temperature. Data herein reported show the effect of pressure, but not temperature, on the recovery correction. However, if a Reynolds number relation exists, then a probe which has an appreciable pressure effect on the recovery correction would also have an appreciable temperature effect.

Conduction Corrections

Consideration of the Mach number, pressure, and temperature effects on the radiation and conduction errors, indicates that for the range in which the probes were tested, the conduction error is negligible when compared with the radiation error. This is the result of a deliberate choice of the highest possible length-to-diameter ratios of the thermocouple consistent with adequate mechanical strength.

Effect of Aspiration Rate

Figure 8 shows the temperature indicated by probe 9 with a variation in the aspiration rate as measured by the pressure drop across the probe (stream total pressure minus pressure measured at point B, fig. 2(i)); probe 8 yielded similar results.

DISCUSSION

The results illustrate quite well that the selection of a probe for a given application involves a compromise among desirable characteristics. For instance, probes 5 and 6, which are suitable as elements for rakes to measure temperature profiles, exhibit very different characteristics. Probe 5 has twice the radiation correction but responds 3 times as fast as probe 6. Probe 7 shows good characteristics in both respects, but is more difficult to fabricate and presents some problems in installation.

Where speed of response is not important, probes 8 and 9 perform as well as the sonic thermocouple in the range of flow conditions covered to within the accuracy of the experiments. These probes, moreover, are easier to construct and are more rugged because the wires are in a low-velocity region. Also they do not require exact positioning of the element (as is the case for the sonic aspirated probe 1) nor demand that a critical pressure ratio be maintained across the probe. Hence, they offer some advantage over the sonic thermocouple in applications where a pressure ratio less than critical is available for aspiration, for example, in the tailpipe of a jet engine where the gases through the probe could be ducted to the exhaust-pressure region. Comparative performance of these probes in more severe requirements, such as very low-pressure combustion studies, would require further investigation.

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In general, the unshielded elements exhibit a larger Δ_0 than the shielded probes (fig. 6). However, the variation of Δ/Δ_0 with pressure for the unshielded elements is less than the variation of Δ/Δ_0 for the shielded probes (fig. 7). The probes reported in reference 5 show similar characteristics. Thus, in application at low pressures the shielded probe can have a recovery error on the same order of magnitude as the unshielded types. This situation is more clearly indicated in table II.

The data clearly show that errors of relatively large magnitude in the measurement of gas temperature may result from neglect of the radiation and recovery corrections for the particular thermocouple probe being used.

The probes described in this report were built for specific applications. These applications determined the dimensions of each type of design. Systematic determination of the optimum value of certain critical dimensions was not made in all cases. In view of these factors, the dimensions given may not necessarily be optimum for the particular design type.

Lewis Flight Propulsion Laboratory
National Advisory Committee for Aeronautics
Cleveland, Ohio, May 28, 1956

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TABLE I. - MEAN VALUES OF K_{rad}^* AND τ_0^*

Probe type	Probe number	K_{rad}^*	τ_0^*
Platinum shielded	2	1.3±0.2	0.80±0.08
Semishielded	3	3.9±0.7	1.3±0.2
Bare-wire crossflow	4	3.6±0.4	0.40±0.03
Unshielded wedge	5	4.8±0.4	0.47±0.02
Shielded wedge	6	2.4±0.2	1.6±0.2
Venturi shielded wedge	7	0.7±0.2	0.24±0.01

TABLE II. - VARIATION OF RECOVERY-CORRECTION FACTOR Δ

WITH PRESSURE AND MACH NUMBER

Probe	Total pressure, atm	Mach number 0.3	Mach number 0.6	Mach number 0.9
1	1.0	0.040	0.040	0.040
	.5	0.037	0.037	0.037
	.2	0.028	0.028	0.028
2	1.0	0.005	0.016	0.027
	.5	0.005	0.016	0.026
	.2	0.005	0.015	0.024
3	1.0	0.001	0.003	0.004
	.5	0.003	0.006	0.010
	.2	0.005	0.011	0.018
4	1.0	0.007	0.025	0.032
	.5	0.007	0.024	0.031
	.2	0.006	0.022	0.029
5	1.0	0.003	0.013	0.021
	.5	0.003	0.013	0.021
	.2	0.004	0.014	0.022
6	1.0	0.001	0.003	0.004
	.5	0.002	0.004	0.006
	.2	0.003	0.007	0.010
7	1.0	0.005	0.016	0.023
	.5	0.005	0.016	0.023
	.2	0.005	0.015	0.021
8	1.0	0.005	0.005	0.005
	.5	0.005	0.005	0.005
	.2	0.004	0.004	0.004
9	1.0	0.005	0.005	0.005
	.5	0.005	0.005	0.005
	.2	0.004	0.004	0.004

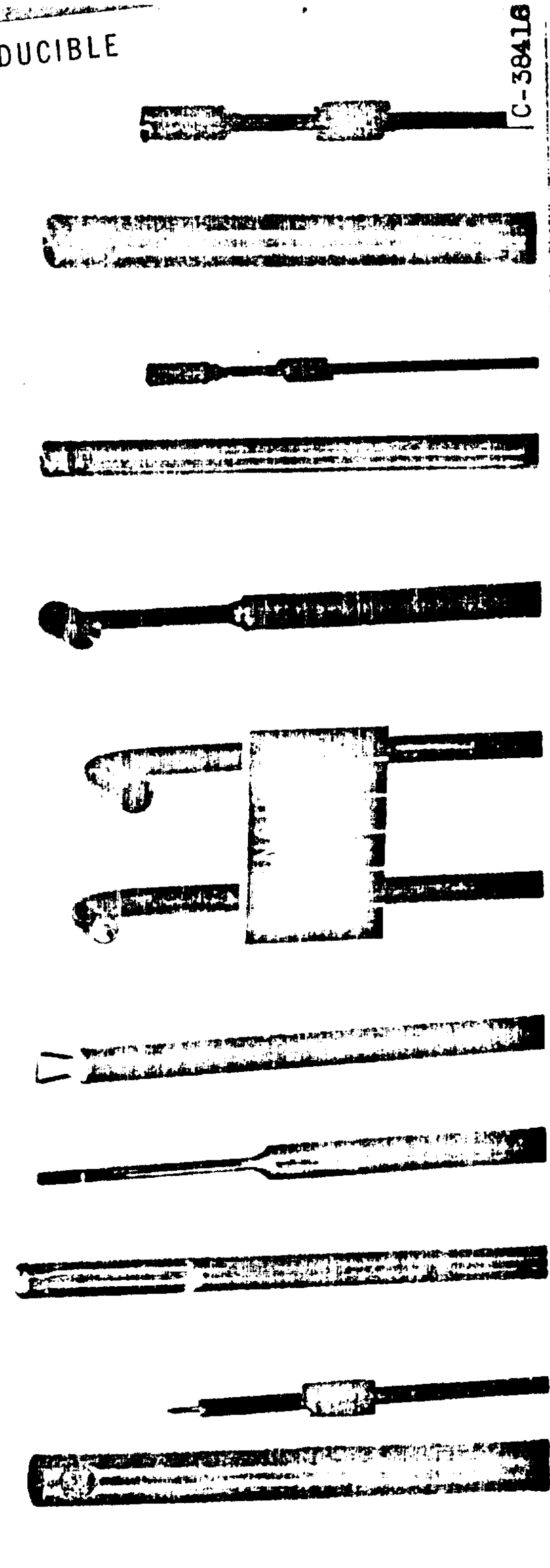

Figure 1. - Probes tested (aspirated probes 1, 8, and 9 with inserts removed).

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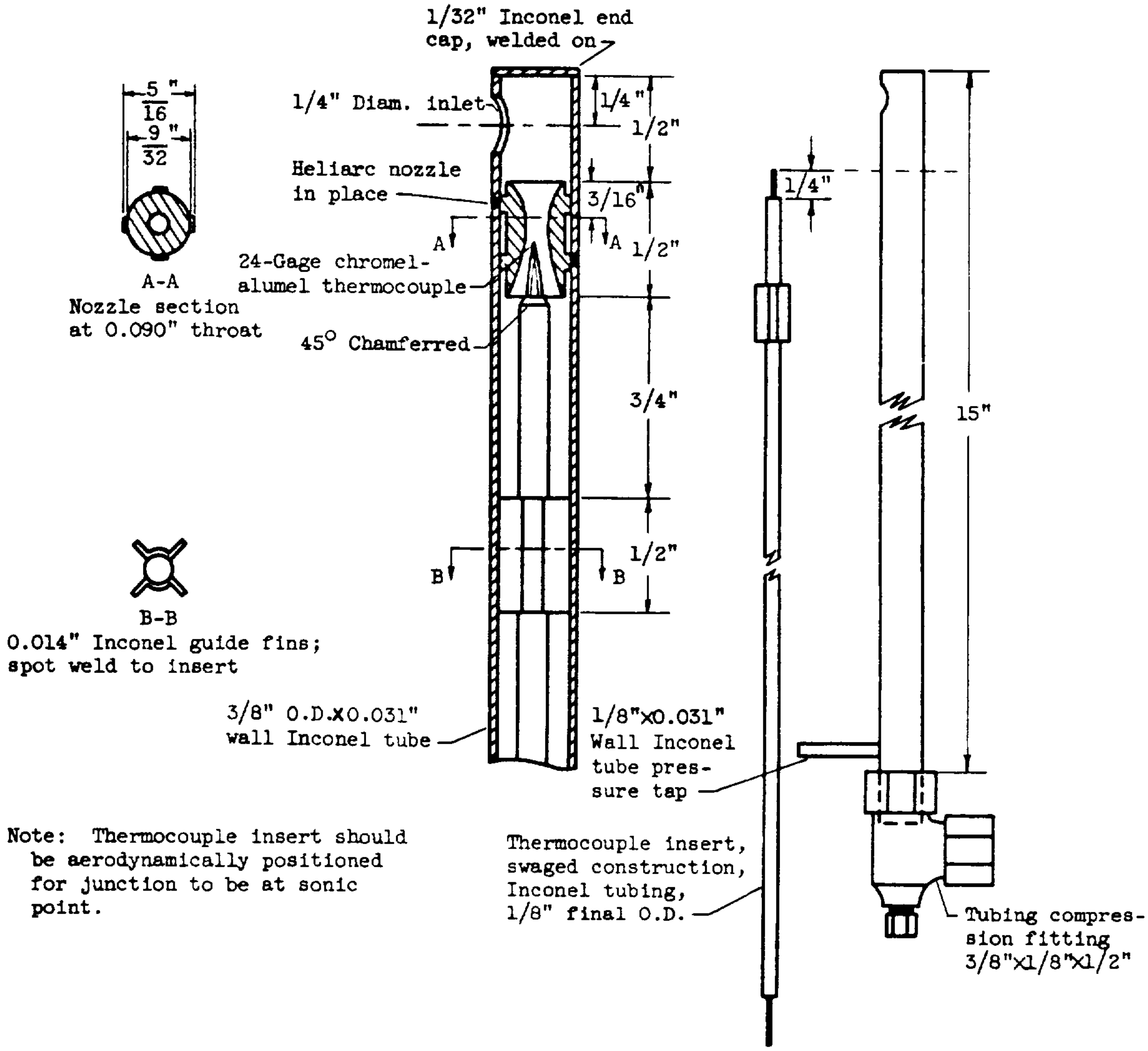
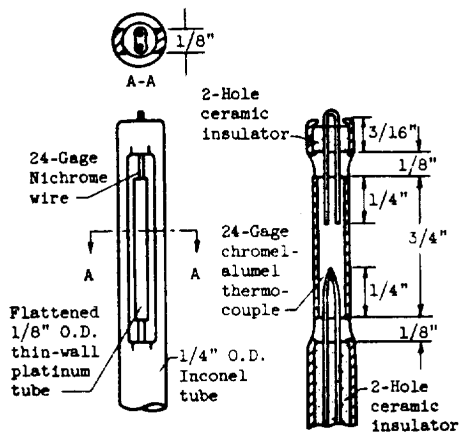
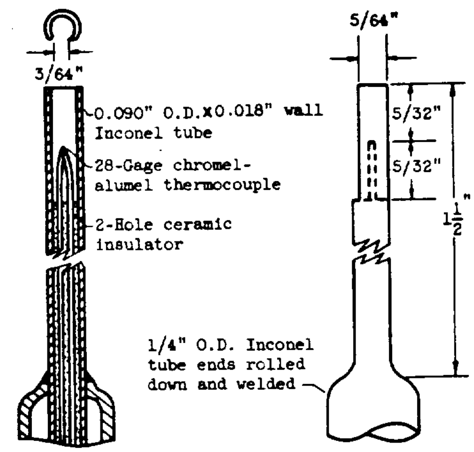


(a) Probe 1. Sonic aspirated.

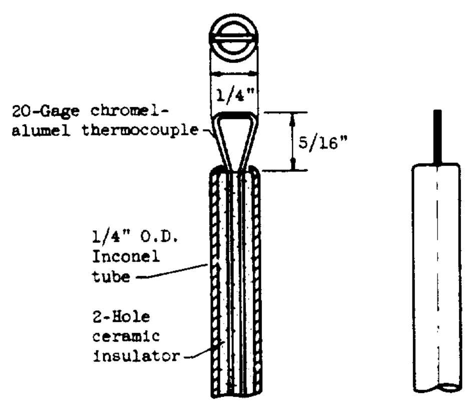
Figure 2. - Probe details.



(b) Probe 2. Platinum shielded.



(c) Probe 3. Semishielded.



(d) Probe 4. Bare-wire crossflow.

Figure 2. - Continued. Probe details.

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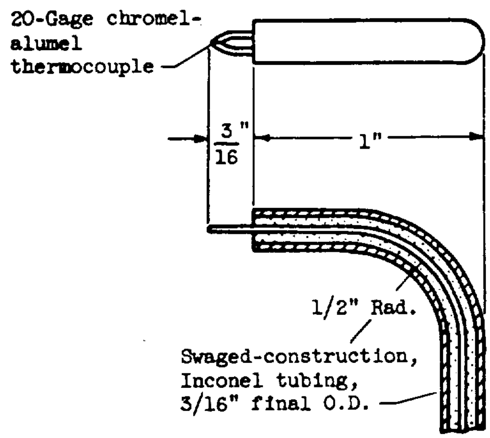
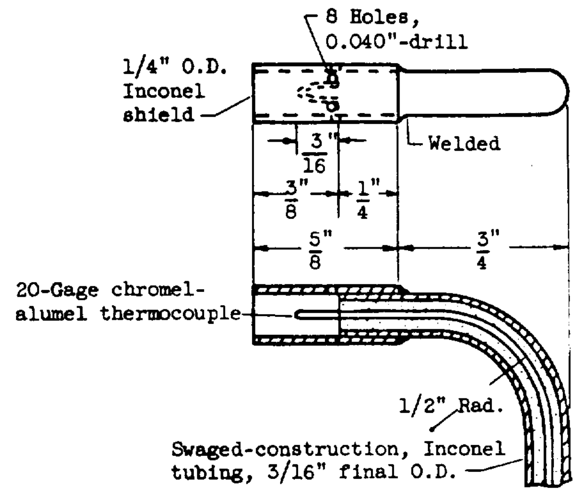
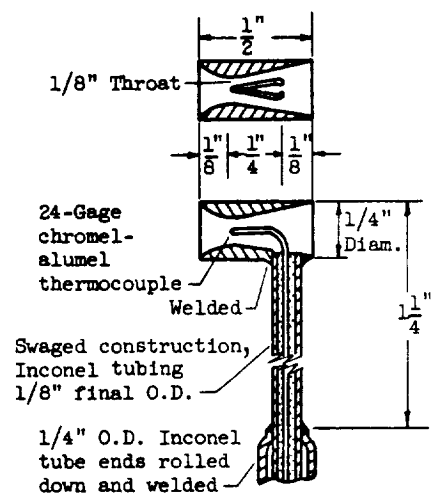


(e) Probe 5. Unshielded wedge.

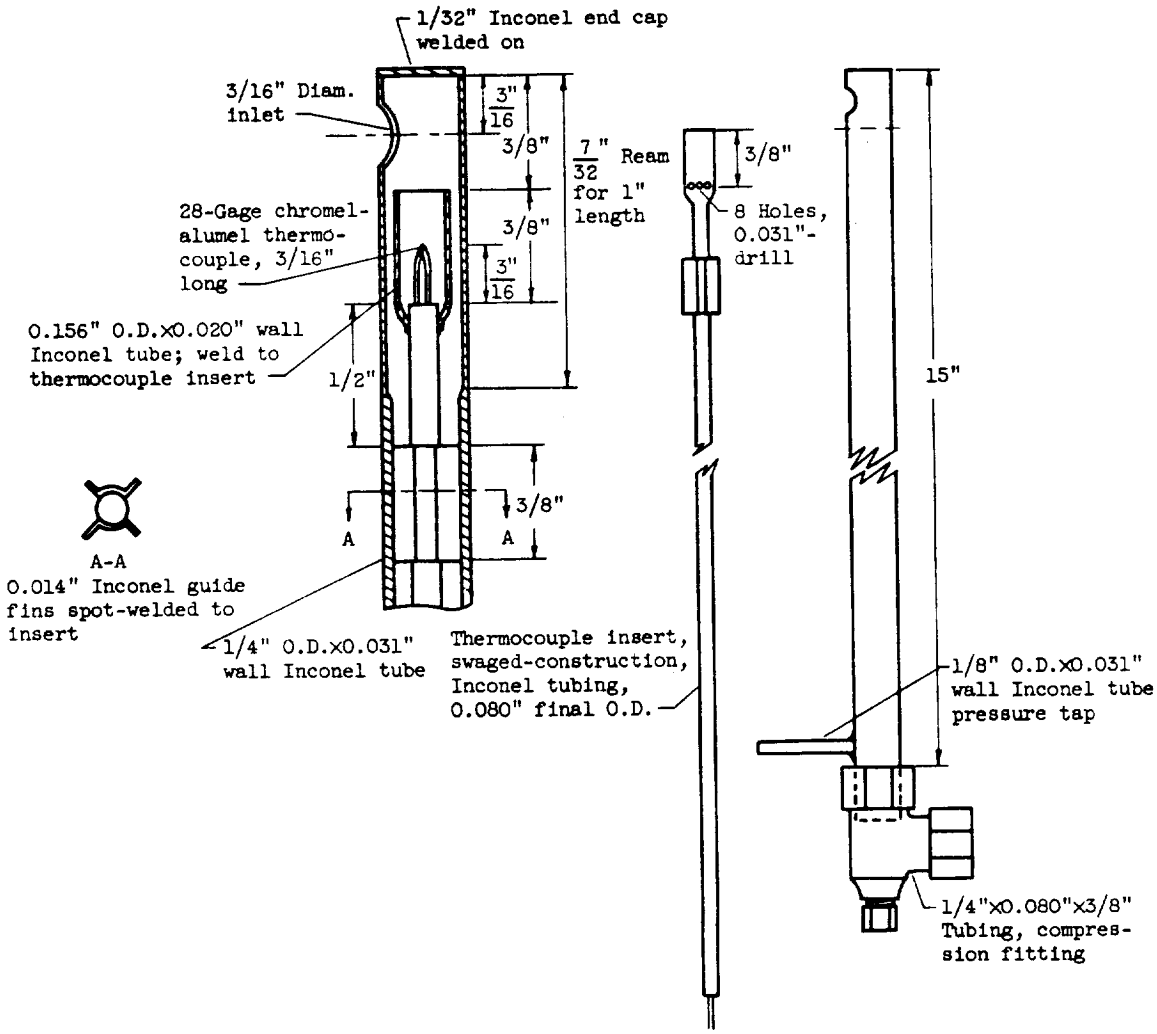


(f) Probe 6. Single-shielded wedge.



(g) Probe 7. Venturi-shielded wedge.

Figure 2. - Continued. Probe details.



(h) Probe 8. Double-shielded aspirated.

Figure 2. - Continued. Probe details.

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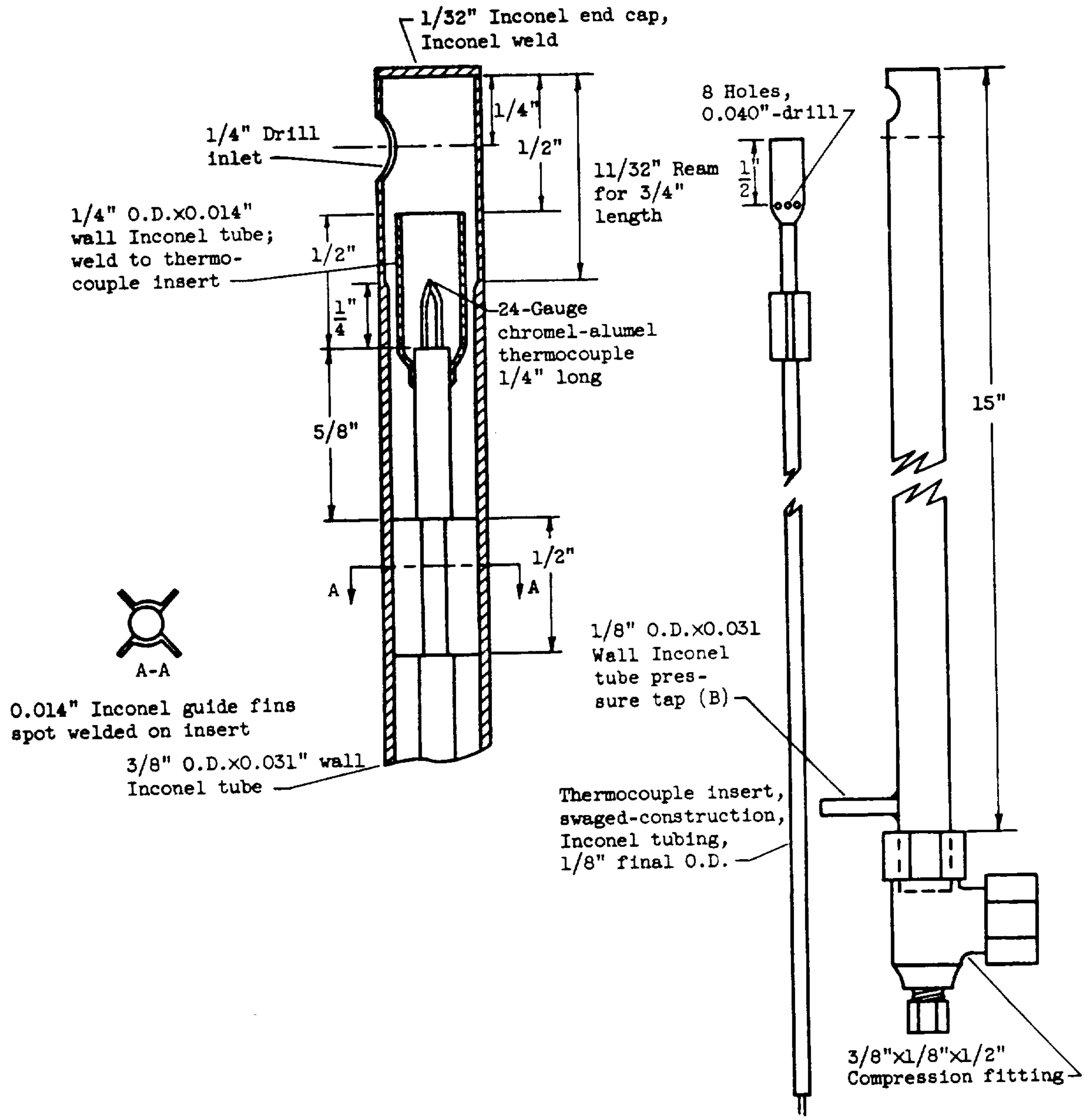

(i) Probe 9. Double-shielded aspirated.

Figure 2. - Concluded. Probe details.

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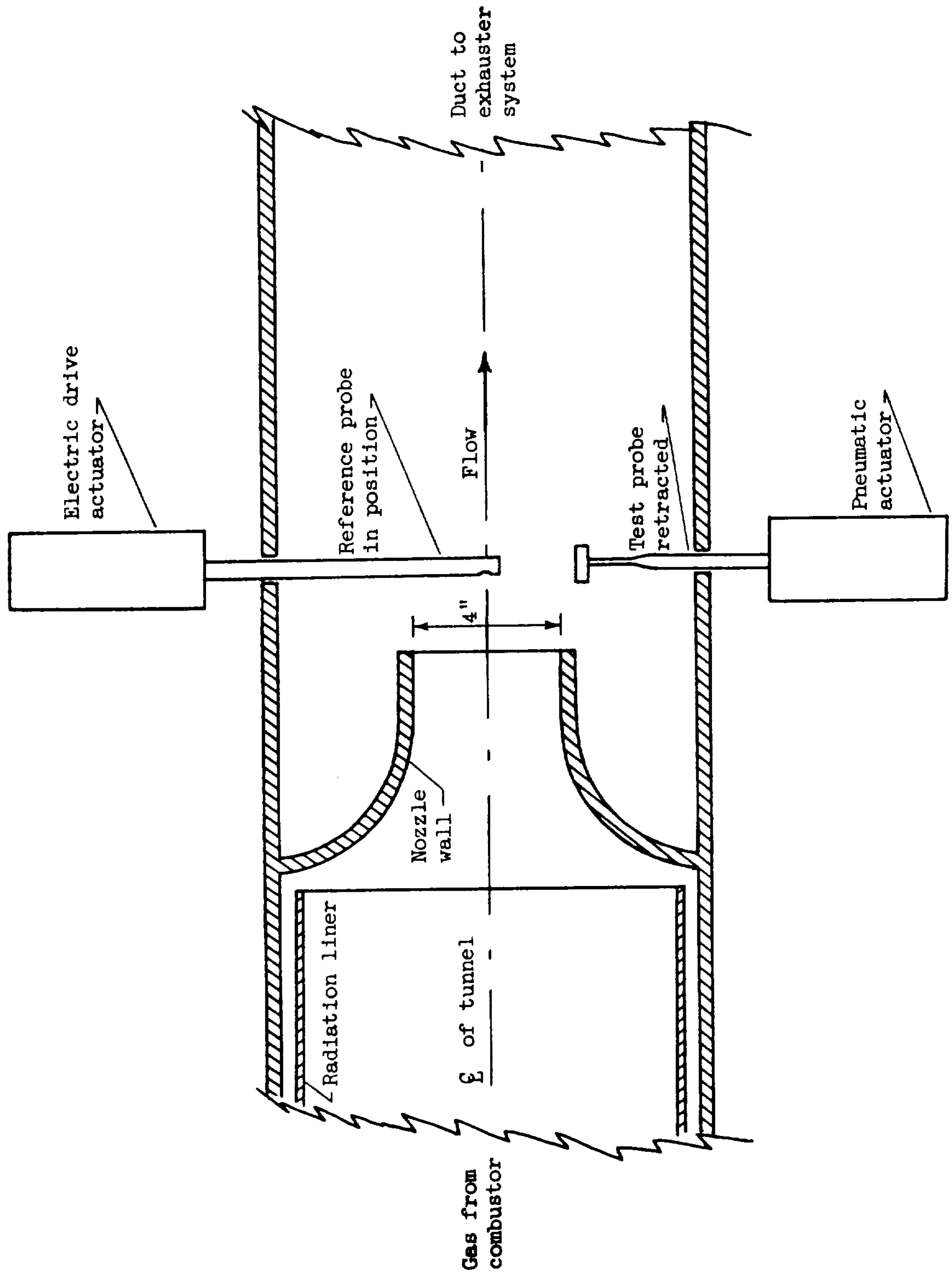

Figure 3. - Arrangement at test section.

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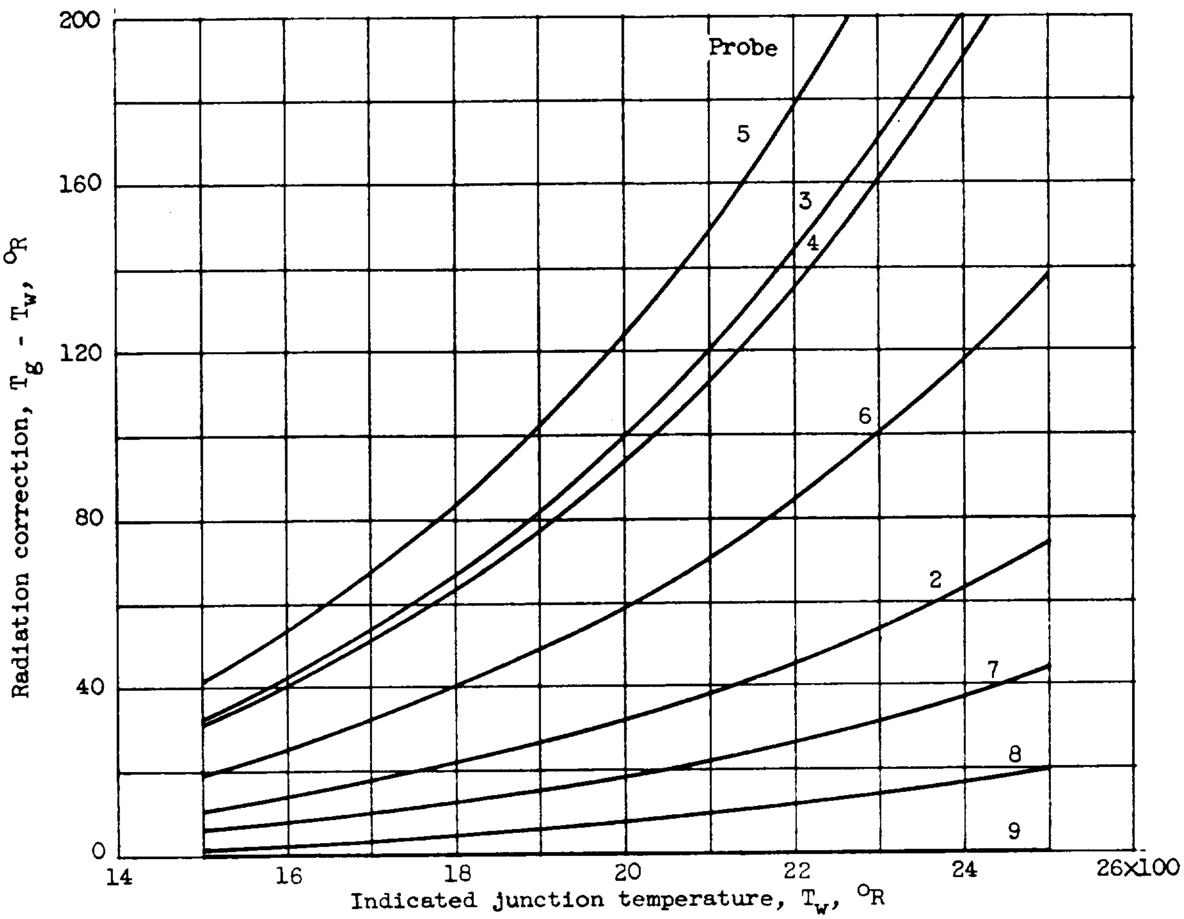

Figure 4. - Radiation corrections. Mach number, 0.3; static pressure, 1 atmosphere; (equivalent duct temperature)^4 << (indicated junction temperature)^4; chromel-alumel wire.

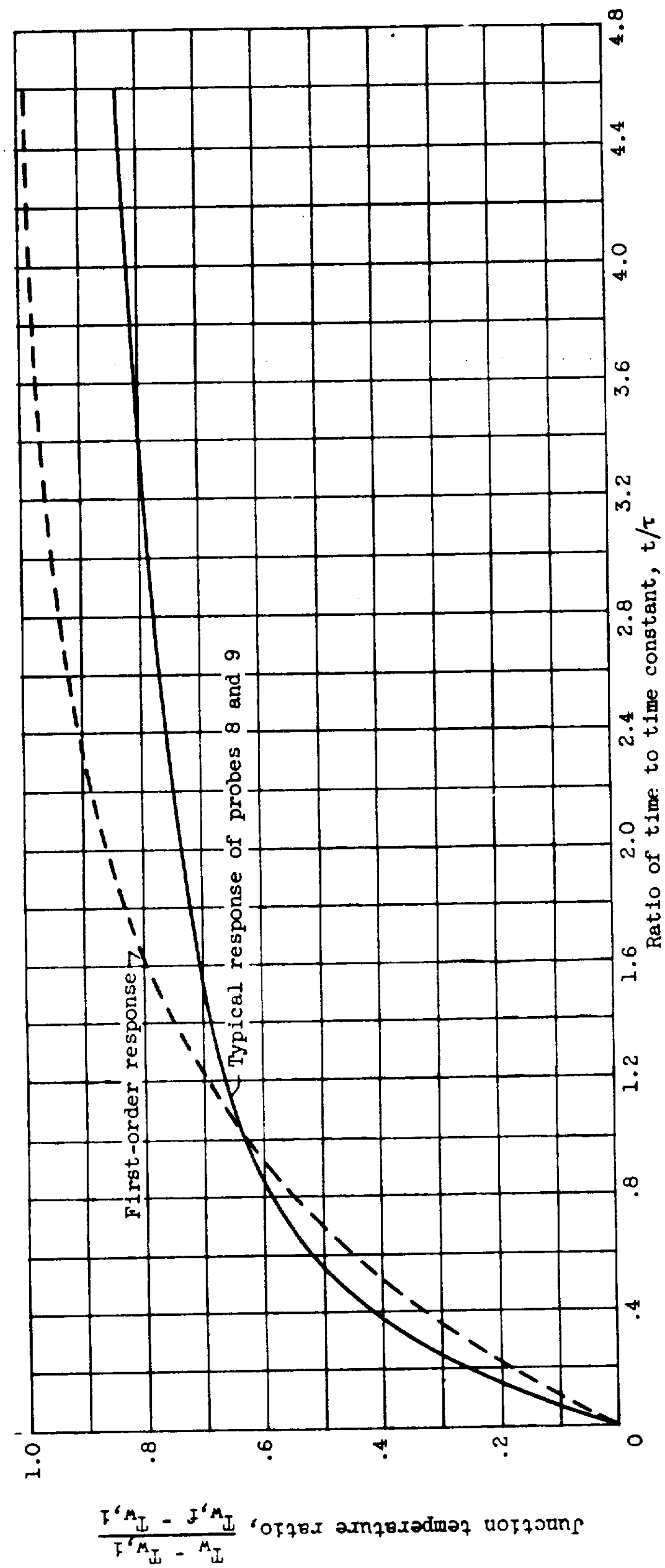

Figure 5. - Typical time response of probes 8 and 9.

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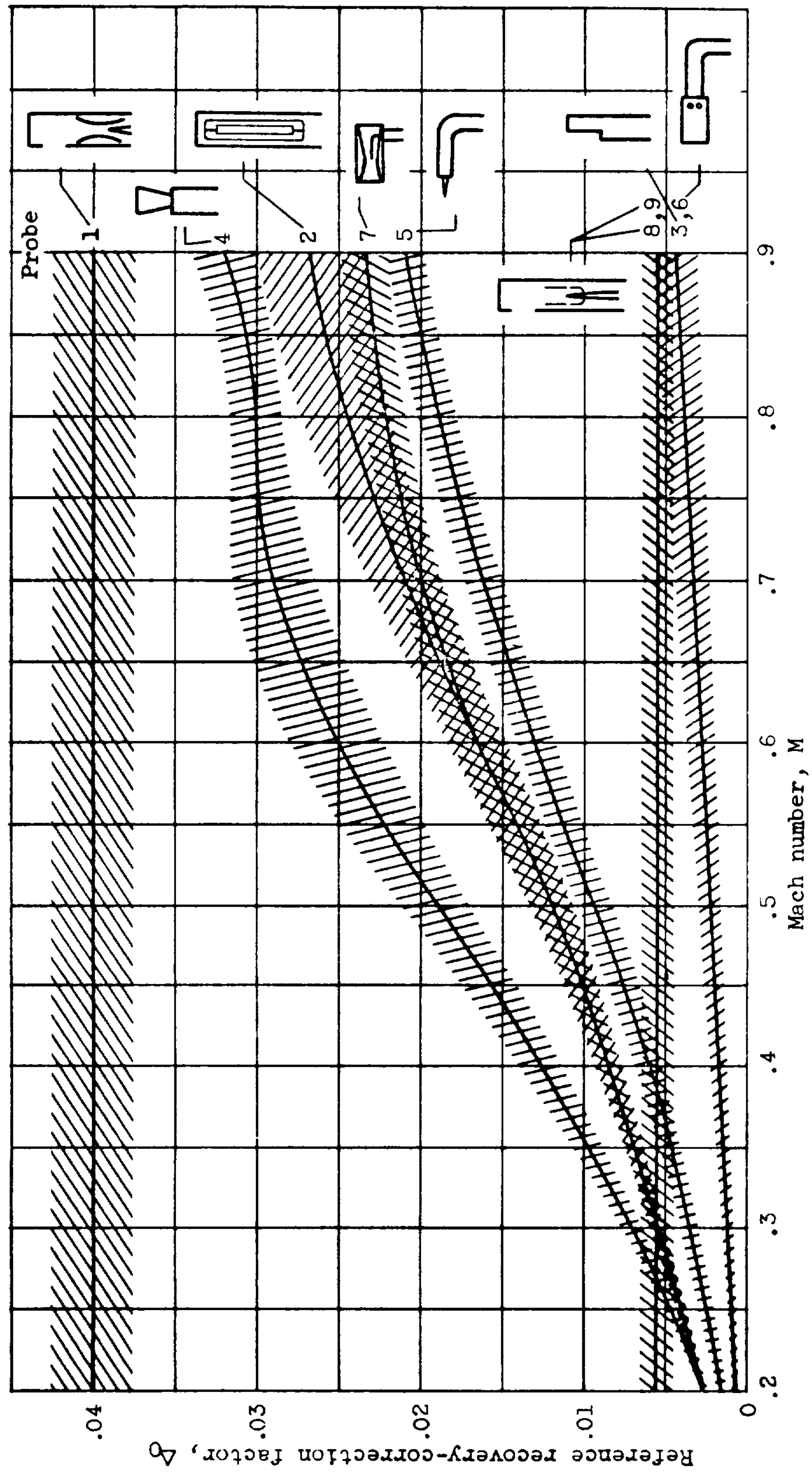

Figure 6. - Variation of reference recovery-correction factor Δ_0 with Mach number, at reference conditions. Total pressure, 1 atmosphere; room total temperature.

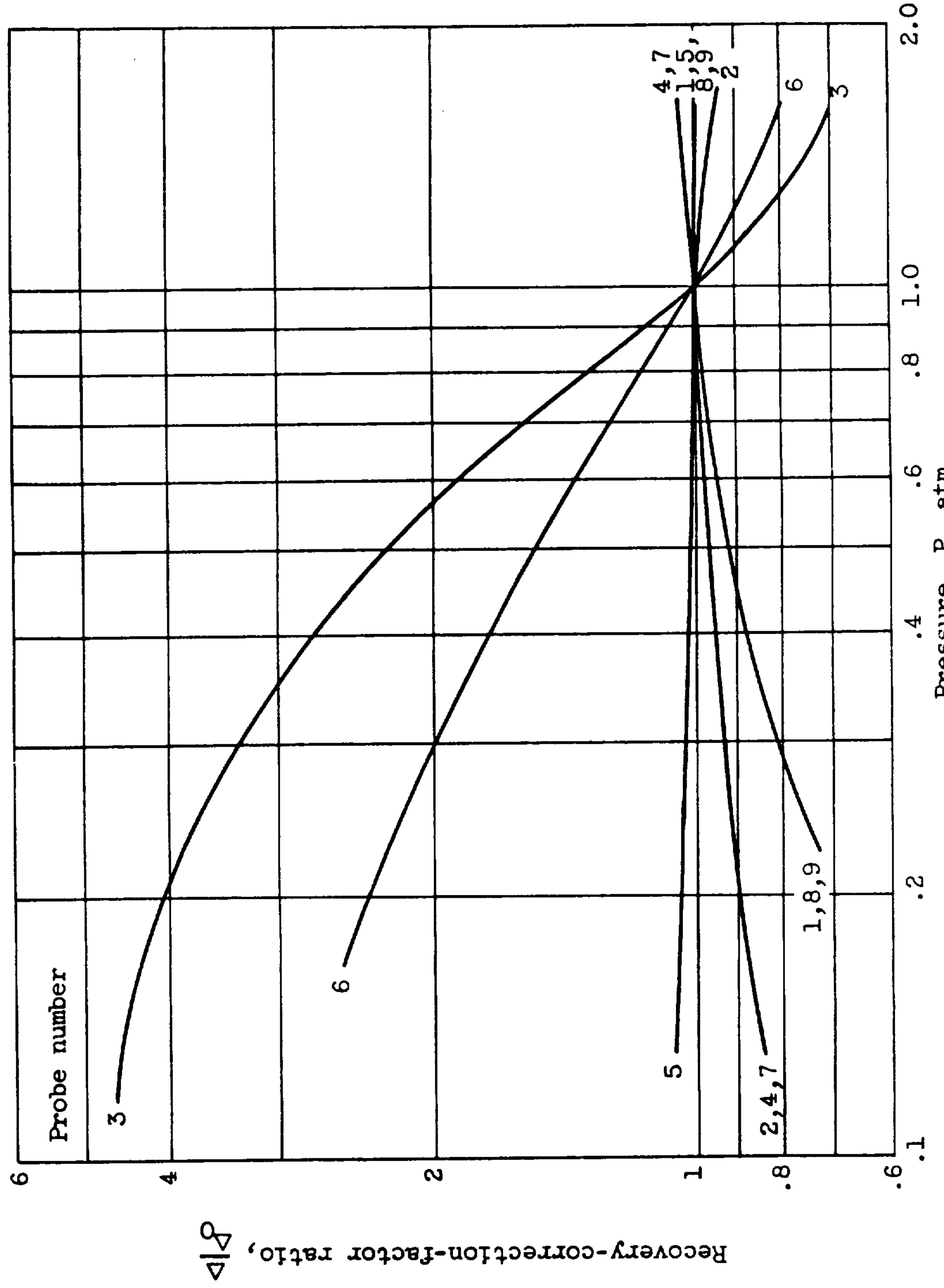

Figure 7. - Variation of recovery-correction factor with pressure.

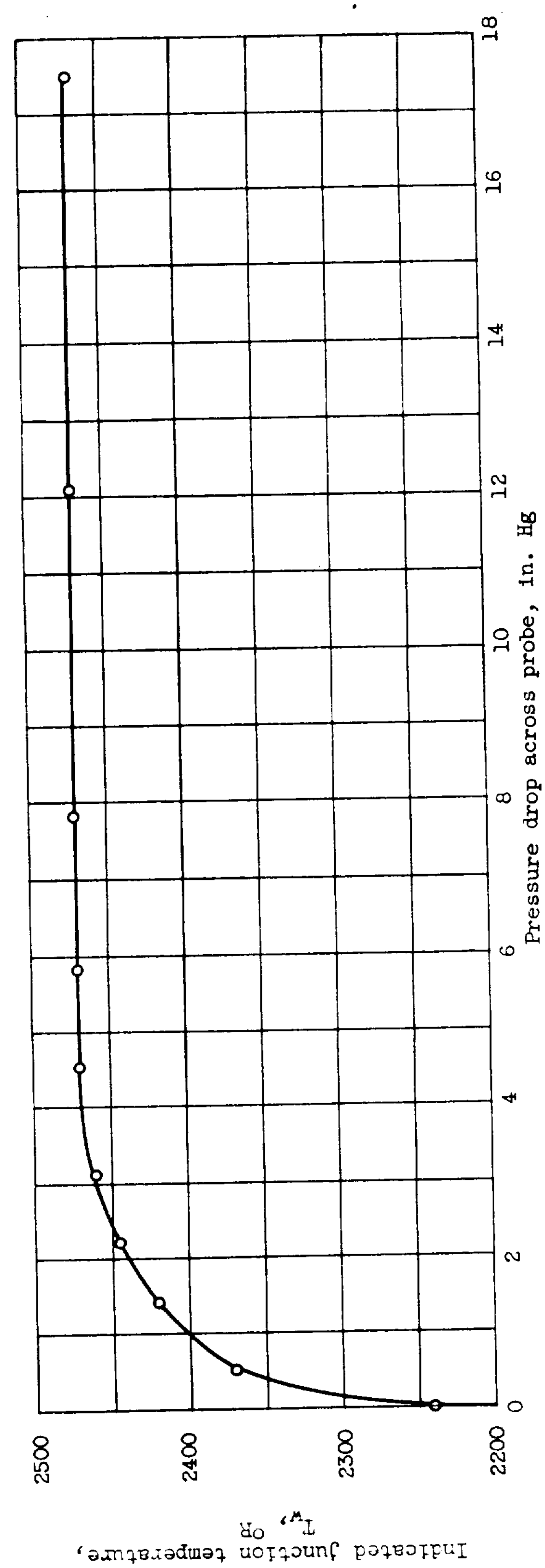

Figure 8. - Indication of probe 9 with variation of aspiration; stream Mach number, 0.35; static pressure, 1 atmosphere.